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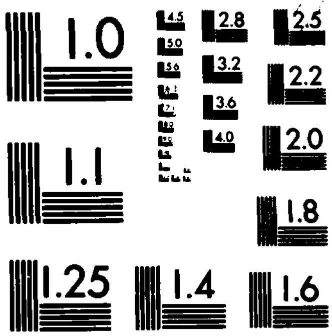

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IN SITU CHARACTERIZATION OF SATURATED SANDS AND SILTS FOR THE PREDICTION OF DYNAMIC SHEAR MODULUS AND SHEAR WAVE VELOCITY

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An electrical method of characterizing coarse-grained soils is described. A non-destructive method of determining dynamic properties of coarse-grained soils is developed based on this fundamental characterization of soils. Correlations are established relating K_2max, coefficient required to obtain dynamic shear modulus to the appropriate electrical parameters. This laboratory correlation was verified by field measurements. A comparison is made between predicted and measured shear wave velocities.

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INSITU CHARACTERIZATION OF SATURATED SANDS AND SILTS FOR THE PREDICTION OF DYNAMIC SHEAR MODULUS AND SHEAR WAVE VELOCITY

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INSITU CHARACTERIZATION OF SATURATED SANDS AND SILTS FOR THE PREDICTION OF DYNAMIC SHEAR MODULUS AND SHEAR WAVE VELOCITY

1. INTRODUCTION

The majority of the numerous analytical methods presently available for assessing the response of soil deposits or soil-structure systems to earthquakes, explosives or machine loadings require an assessment of the shear modulus G_{max} at shear strain amplitudes less than .001 percent. Field values of G_{max} are used directly to determine soil stiffness for low amplitude vibration studies (Richart et.al., 1970). For high amplitude studies, field values of G_{max} are used as reference values (Seed et.al., 1970). Geophysical methods utilizing cross hole or down hole technique are often used for critical soil analyses. However, in certain situations empirical equations or laboratory testing methods are used to determine G_{max}.

Empirical equations used for sands are:

$$G_{max} = 1230 \; \frac{(2.97-e)^2}{1+e} \; (\bar{\sigma}_o)^{1/2} \qquad \text{Hardin and Black (1968,1969)} \qquad (1)$$

$$G_{max} = 1000 \; K_{2max} \; (\bar{\sigma}_o)^{1/2} \qquad \text{Seed and Idriss (1970)} \qquad (2)$$

$$G_{max} = 1220 \; N^{0.8} \qquad \text{Ohsaki-Iwasaki (1973)} \qquad (3)$$

Where e is the void ratio, $\bar{\sigma}_o$ is the mean effective confining pressure in psi for the Hardin-Black equation, and in psf for the Seed-Idriss equation, K_{2max} is an empirical factor which varies according to the relative density, N is the standard penetration value and G_{max}, in the Ohsaki-Iwasaki equation, is in t/m^2.

Equation (3) suffers limitation associated with an erratic procedure. In particular, the values of N can vary as much as fifty percent and hence it is not considered further in this study.

Equations (1) and (2) give similar results; Seed's and Idriss' procedure for the verification of equation (2), used in part the data developed by Hardin and Black. Equation (2) will be considered for further laboratory correlation.

Investigations have shown that modulus values for sands are strongly influenced by the confining pressure, the strain amplitude, the void ratio, and the angularity of the particles at low confining pressures; they are however not significantly affected by grain size characteristics. Very limited data is available to indicate the influence of anisotropy on G_{max}. Thus it can be argued that the parameter K_{2max} in equation (2) is a function of porosity, shape, and orientation of particles and that G_{max} is a direction dependent property. K_{2max} also depends on cementation of particles as pointed out by Seed and Idriss (1970). Thus, to completely characterize a sand taking into consideration porosity, shape, orientation of particles, anisotropy and cementation, a methodology is needed so that K_{2max} values, obtained from in situ shear wave velocities measurements, can be correlated with the structural characteristics to predict shear wave velocity. It is the purpose of this study to use the recently developed methodology of characterizing sands by electrical methods to develop such a correlation.

2. NON DESTRUCTIVE METHOD TO CHARACTERIZE GRAIN AND AGGREGATE PROPERTIES OF SANDS AND SILT

It is generally accepted that the derived properties of sand deposits are governed by the grain and aggregate characteristics of the particles. It has been shown experimentally by numerous studies carried out by Archie (1942), Jackson (1975), Wyllie and Gregory (1953), Arulanandan (1975), Arulanandan and Kutter (1978), Kutter (1978), and Arulmoli (1980), that a nondimensional electrical parameter called the Formation Factor is dependent upon particles' shape, long axis orientation contact orientation and size distribution and also void ratio, cementation, degree of saturation and anisotropy. The formation factor, F, is defined as the ratio of the conductivity of the electrolyte, σ_s, to the conductivity of the saturated sand-solution mixture, σ_m. The dependence of formation factor on void ratio, particles' shape and long axis orientaton has been theoretically shown by Arulanandan and Dafalias (1979) and Dafalias and Arulanandan (1978). It has also been shown from thin section studies and formation

factor measurements in different directions that the structure of sand mass in most cases is transversely isotropic, with the vertical axis being the axis of symmetry, both in natural deposits and in samples prepared in the laboratory. However, in certain situations, the manner in which the sand deposit is formed may cause the sample to be orthotropic. But to a close approximation, it is reasonable to consider the structure of the sand mass to be transversely isotropic.

The formation factor, when suitably interpreted, can be used to quantify and predict the porosity, shape and anisotropy of sand deposits. For example, an average formation factor $\bar{F}$ given by

$$\bar{F} = (F_V + 2F_H)/3 \quad \ldots\ldots\ldots\ldots \quad (4)$$

with F_V and F_H being the vertical and horizontal formation factors respectively, has been shown, both by theory and by laboratory measurements, to possess the properties of the first invariant of a second order tensor. A tensor is defined as a quantity having physical significance whose components with respect to a coordinate system transform according to a specific law upon change of the coordinate system. A second order tensor has nine components. Tensor transformations are linear and homogeneous and hence if tensor equations are valid in one coordinate system, they are valid in any other coordinate system. This invariance of tensor equations under a coordinate tranformation is one of the principal reasons for the usefulness of tensor methods in applied mechanics. It has been shown that $\bar{F}$ is independent of anisotropy caused by preferred particles' orientation and is a direct measure of porosity, n, for a given sand. To illustrate this, horizontal and vertical formation factor measurements on lucite balls and Monterey '0/30' sand samples, prepared by three different methods, were made in laboratory. Monterey '0/30' sand is uniformly graded and lucite balls are 1/8 inch diameter spheres. Two six inch cubical cells, one with two six inch squares platinum coated copper electrodes fixed on two opposing vertical faces and the other with electrodes on the top and bottom faces have been used for making horizontal and

vertical electrical resistance measurements respectively. The formation factor values were calculated using the following equations;

$$F = \frac{\sigma_m}{\sigma_s} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

and

$$\sigma_s = \frac{1}{R} \cdot \frac{L}{A'} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

where R is the resistance, L is the distance between the electrodes and A' is the area of the electrodes. The resistance measurements were made to half a present accuracy. $\bar{F}$-n relationships for all three methods were seen to be identical and are shown in Figs. 1 and 2 for lucite balls and Monterey '0/30' sand respectively. Five more uniform sands and a silty sand from the Revelestoke dam site were also used in the study and unique relationship between $\bar{F}$ and n was found to exist for each sand. The $\bar{F}$-n curves for all the sands and lucite balls are shown in a Log-log plot in Fig. 3. It would appear that the average formation factor for any type of sand describes the state of packing of sand and is independent of the long axis orientation of the particles.

The unique relationship between $\bar{F}$ and n can be used to predict in situ porosity of uncemented sands. The accuracy of the use of this method for in situ prediction of the porosity of cemented sands needs to be investigated.

2.1 Shape Factor and Anisotropy Index

An integration technique proposed by Bruggeman (1935) was used by Dafalias and Arulanandan (1975,1978) to derive an expression for average formation facotr, $\bar{F}$, as a function of porosity, n, and average shape factor, $\bar{f}$, as

$$\bar{F} = n^{-\bar{f}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

The average shape factor $\bar{f}$ is the negative slope of the log $\bar{F}$-Log n plot. It is the first invariant of the second order shape factor tensor f and it relates the electric

fields inside and outside the sand particles. It has been shown both theoretically and experimentally that the shape factor is directional dependent and depends on porosity, gradation and particles' shape and orientation Arulmoli (1980), Dafalias et al (1979), Kutter (1978). Since the average formation factor is independent of orientation of particles, the average shape factor, for a given sand, is expected to be a function of porosity and the shape of particles. A mean value of the average shape factor, $\bar{f}_{mean}$, defined as

$$\bar{f}_{mean} = \frac{1}{2} (\bar{f}_{max} + \bar{f}_{min}) \quad \text{.......................... (8)}$$

where $\bar{f}_{max}$ and $\bar{f}_{min}$ are the extreme values of $\bar{f}$ at extreme porosities, is used in the correlations proposed in this paper. The maximum percentage difference between $\bar{f}_{max}$ and $\bar{f}_{min}$ is about five percent, Arulmoli (1982).

An anisotropy index A was introduced by Arulanandan and Kutter (1978) as

$$A = (F_V/F_H)^{1/2} \quad \text{.................... (9)}$$

Anisotropy of sand structure is due to the orientation of individual particles and the contact orientation. Formation factor measurements made on samples consisting of spherical particles showed anisotropy for certain structural arrangements. Even though spherical particles do not have any preferred orientation, the contact orientation was significant enough to produce anisotropy in structure. Formation factor measurements are thus, sensitive to contact orientation of particles, in addition to the orientation of individual particles. This has been elaborated theoretically in detail by Dafalias and Arulanandan (1979). Dependence of formation factor on cyclic stress history has also been shown by Arulmoli (1980). If the samples of sands are consolidated under different anisotropic stresses, it is reasonable to assume that the formation factors will be different for different stress conditions. This difference is expected to be due to the particle and contact orientations being different from different stress conditions.

2.2 Overall Indices of Soil Characteristics

It is seen from Fig. 4 that the derived porosities of a sand deposit are governed by the grain and aggregate characteristics of the particles. It is clear from the foregoing paragraphs that the formation factor depends on these characteristics and hence electrical parameters obtained using formation factors of sands in different directions may be used to correlate with soil properties such as liquefaction potential, friction angle, permeability and compressibility. The parameters $\bar{F}$, $\bar{f}_{mean}$ and A may be combined to obtain such correlations. These empirical correlations would be extremely useful in evaluating the performance of sites which contain sand deposits.

2.3 Electrical Probe

Field values of formation factors were obtained using an electrical probe, Geoelectronics Model GE-100, shown in Figure 5 (Arulanandan (1977)). The probe consists of three main parts:

1. The main body is a 4 feet long hollow steel tube with a 3 inch outside diameter and a wall thickness of 1/8 inch. An electrical bridge is housed inside the main body together with a 12 volt gear pump to pump solution into a cell for solution conductivity measurements. The bridge can resolve resistance to an accuracy of about one percent.
2. The probe tip is a 12 inch long steel tube with a 3 inch outside diameter and 1/16 of an inch wall thickness. The probe tip carries the electrodes for sample measurements in two different directions, Figure 6. A tiny open cell with electrodes is also located along the outside wall of the probe tip and it is covered with a porous stone. The probe tip can be unscrewed from the main body and is replaceable.
3. The control unit consists of a microprocessor for transmitting the electrical signal and receiving the response of the material within the probe tip in the form

of resistances and capacitances. The control unit is connected to the electronics in the main body through a 150 foot long stiff cable. The whole probe assembly can be operated with a 12 volt d.c. power source.

3. LABORATORY CORRELATION BETWEEN ELECTRICAL PARAMETERS AND SHEAR MODULUS

One way of predicting maximum shear modulus, G_{max}, is by measuring the in situ shear wave velocity, V_s, and by using the equation

$$G_{max} = \rho \, V_s^2 \quad \ldots\ldots\ldots\ldots \quad (10)$$

where ρ is the mass density of the deposit at the depth of measurement. Investigations have shown that the maximum shear modulus values for sands are strongly influenced by the confining pressure and the void ratio. A relationship between the shear modulus, G, in psf, and mean effective confining pressure, $\bar{\sigma}_o$, in psf, was given by Seed and Idriss (1970) as (2):

$$G = 1000 \; K_2(\bar{\sigma}_o)^{1/2} \quad \ldots\ldots\ldots\ldots \quad (11)$$

where the parameter K_2 depends on the void ratio, strain amplitude, geological age of the sand mass and in situ stresses. Thus, the maximum shear modulus at very low shear strain amplitudes is related to $\bar{\sigma}_o$ through K_{2max}, the maximum value of K_2, and is given by equation (2)

$$G_{max} = 1000 \; \partial \; K_{2_{max}} \; (\bar{\sigma}_o)^{1/2} \quad \ldots\ldots\ldots\ldots \quad (2)$$

In the equation (2), K_{2max} depends largely on void ratio and also on the age of the deposit. Field and laboratory shear wave velocity measurements were made using cross hole and down hole seismic measurements and the electrical measurements were made in the field and in the laboratory using the electrical probe. Shear wave velocity measurements in the field, were made at three sites: El Centro Site (Ertec report (1982)), Lawsons's Landing Site at San Francisco (Kleinfelder and Associates

(1981)), and Tientsin Site in People's Republic of China (Arulanandan (1982)), and laboratory measurements made on Ottawa C109 and soil from Lawson's Landing site were used to establish a correlation between K_{2max} obtained from equation (2) above and an electrical parameter. The electrical parameter $\overline{F}/(A \cdot \overline{f}_m)^{1/2}$ was found suitable to correlate with K_{2max}.

The field results are the laboratory results of shear wave velocities and the electrical properties are given in Table 1, 2, 3 and 4. The gradation characteristics of the sands and the laboratory values of electrical properties are given in Figs. 7, 8, and 9. The correlation between K_{2max} and $\overline{F}/(A \cdot \overline{f}_m)$ is given in Fig. 10.

In situ measurements of the formation factors in the horizontal and vertical directions enable us to determine $\overline{F}$, and A and laboratory determination of $\overline{F}$-n relationship would give us $\overline{f}_{mean}$ and hence K_{2max} can be predicted using the relationship shown in Fig. 10. The value of G_{max} can be calculated from equation (2) for the depth of the deposit under consideration.

A typical example of the comparison between the measured and predicted shear wave velocities with depth using the above procedure is shown in Fig. 11.

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Table 1. Electrical and Shear Wave Velocity Field Measurements for El Centro Site

$f_m = 1.142$

B•H#	Depth (ft)	$\bar{F}$	A	$\frac{\bar{F}}{(A \cdot \bar{f}_m)^{1/2}}$	Measured V_s	K_{2max}
					V_s (ft/sec)	K_{2max}
1	10.5	2.82	2.409	420	22.9	
	12.5	2.96	1.118	2.620	440	24.2
	14.5	3.17	1.143	2.775	460	25.5
	16.5	3.86	1.090	3.460	545	34.6
	20.5	3.67	1.100	3.274	650	46.5
2	10.75	2.10	0.892	2.081	420	22.8
	12.0	2.83	1.226	2.391	440	24.4
	14.5	3.29	1.106	2.927	460	25.5
	16.5	3.42	1.193	2.920	545	34.7
3	9.75	2.63	0.880	2.624	420	23.2
	12.0	3.00	1.187	2.577	440	24.5
	14.0	2.91	1.056	2.650	440	23.6
	16.0	2.91	1.142	2.540	530	33.1
4	10.5	2.93	1.126	2.584	420	22.9
	12.0	2.70	1.242	2.267	440	14.8
	14.25	3.53	1.176	3.046	450	24.5
	16.5	3.13	1.118	2.770	545	34.6

Table 2. Electrical and Shear Wave Velocity Field Measurements for Lawson's Landing Site at San Francisco

$f_m = 1.506$

Depth (ft)	$\bar{F}$	A	$\bar{F}/(A \cdot \bar{f}_m)^{1/2}$	Measured V_s V_s (ft/sec)	K_{2max} K_{2max}
10	3.41	1.034	2.733	400	28
15	3.56	1.034	2.853	480	34
20	3.56	1.034	2.853	560	41

Table 3. Electrical and Shear Wave Velocity Field Measurements for Tientsin Site at People's Republic of China

B.H #	Depth	$\bar{F}$	n	A	$\bar{f}$	$\bar{F}/(A \cdot \bar{f}_m)^{1/2}$	Measured V_s and K_{2max}	
							V_s (ft/sec)	K_{2max}
y_{24}	4.9	4.4	0.46	1.07	1.91	3.08	400	44.5
	8.9	5.6	0.46	1.12	2.10	3.65	600	66.6
Y_{29}	7.2	3.20	0.480	1.05	1.58	2.48	420	29.2
	9.2	3.70	0.479	1.15	1.78	2.59	445	29.6
	10.8	3.40	0.420	1.25	1.41	2.56	445	28.5
Y_{21}	13.1	2.90	0.449	1.12	1.33	2.38	385	23.1
	18.0	4.34	0.450	1.00	1.84	3.20	550	41.5
	23.0	5.42	0.440	0.98	2.06	3.81	715	63.2
F_{13}	16.4	3.25	0.480	1.11	1.61	2.42	460	29.4

Table 4. Shear Wave Velocity Predictions and Measurements for Laboratory Tests

Soil Type	$\bar{F}$	A	$\bar{F}/(A \cdot \bar{f}_m)^{1/2}$	Shear Velocity Measured	K_{2max}
Ottawa C-109 Sand	3.65	1.01	3.090	200	52
$\bar{f}_m = 1.381$	4.25	1.01	3.598	310	75
Lawson's Landing	3.98	1.070	3.135	260	47
Site Sand	4.62	1.076	3.629	310	66
$\bar{f}_m = 1.506$					

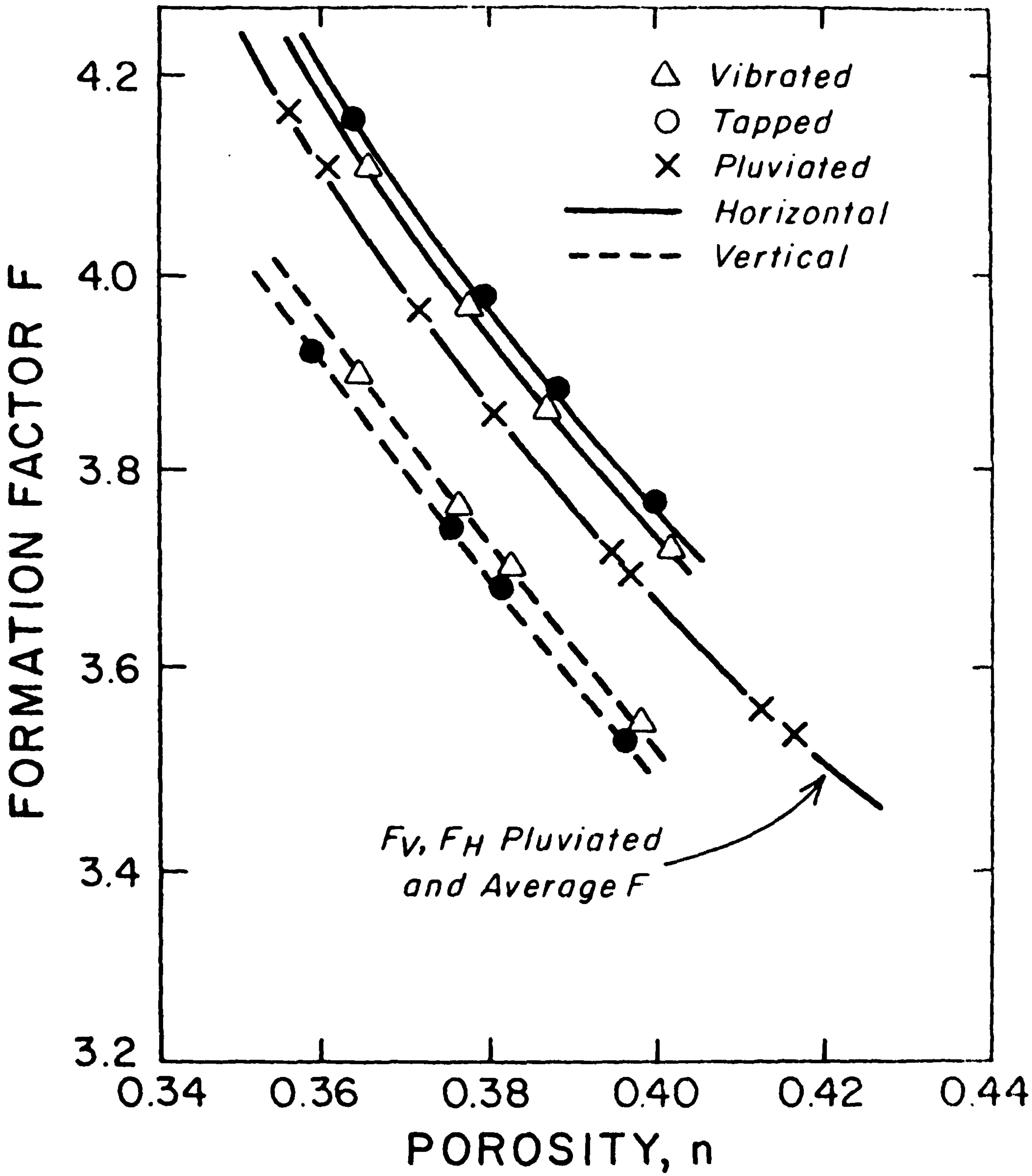

Fig 1. Formation Factor and Porosity Relationship for Lucite Balls

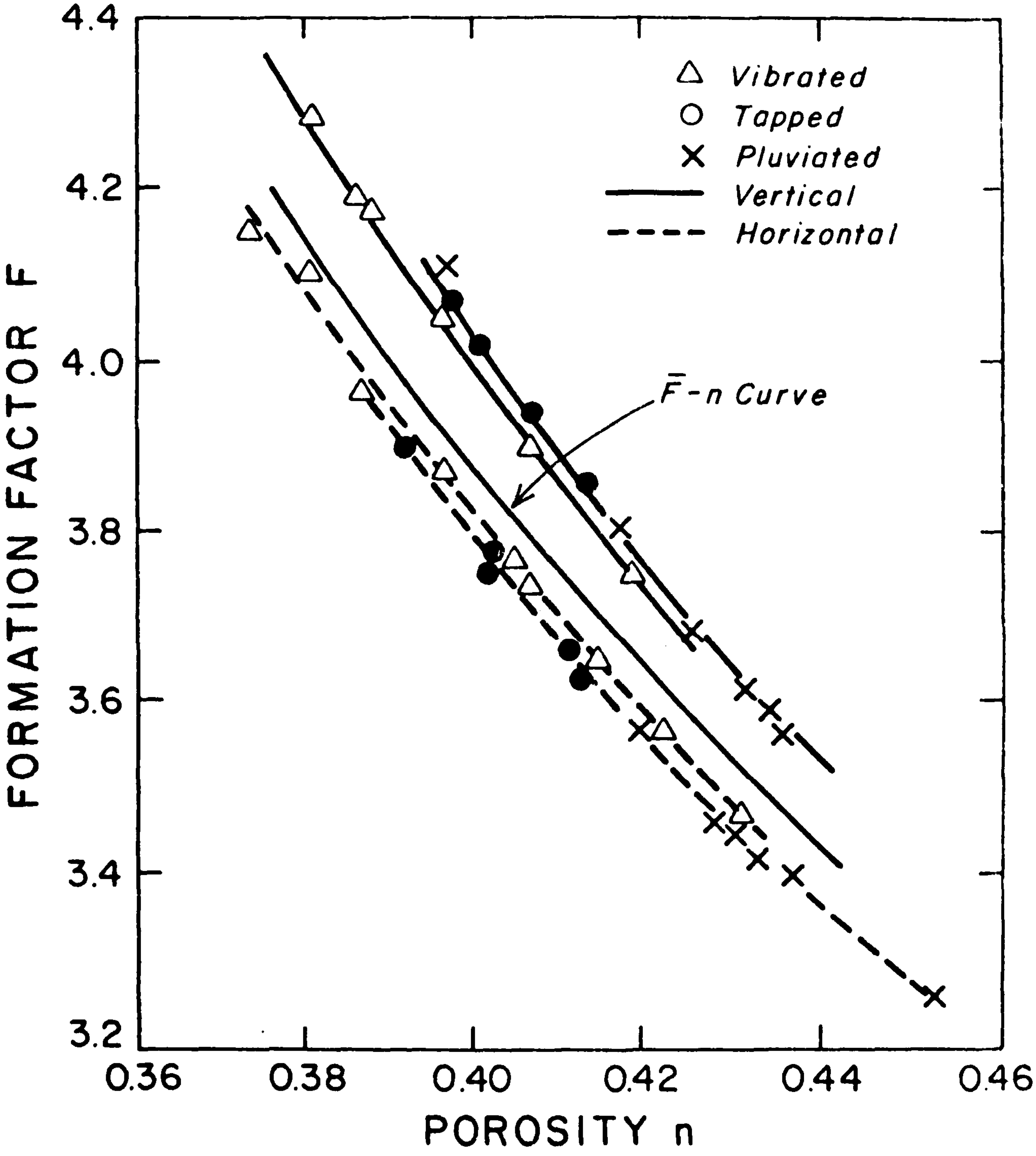

Fig 2 Formation Factor and Porosity Relationship for Monterey '0/30'

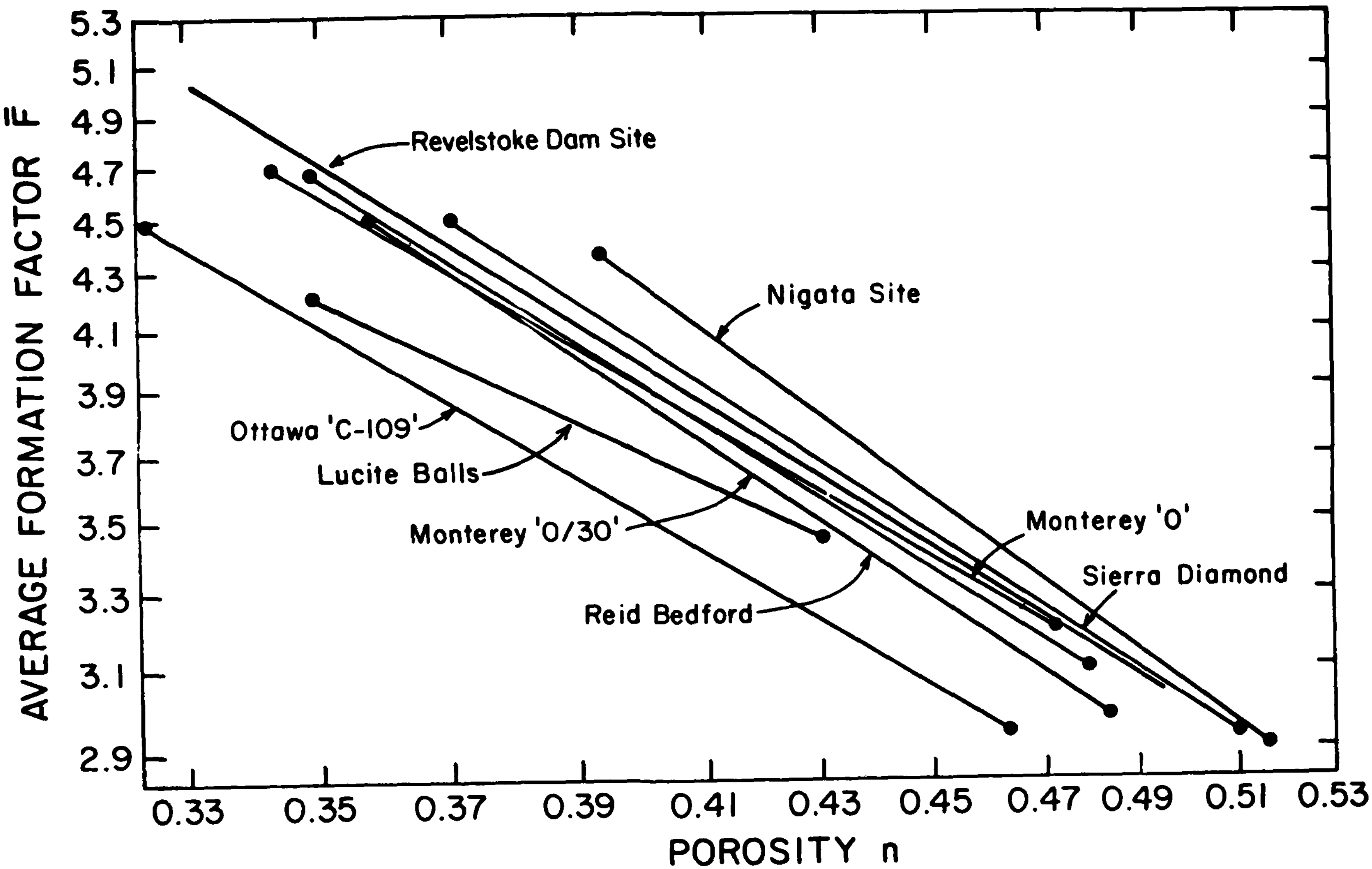

Fig. 3 Log F-Logn curves for five sands and lucite balls

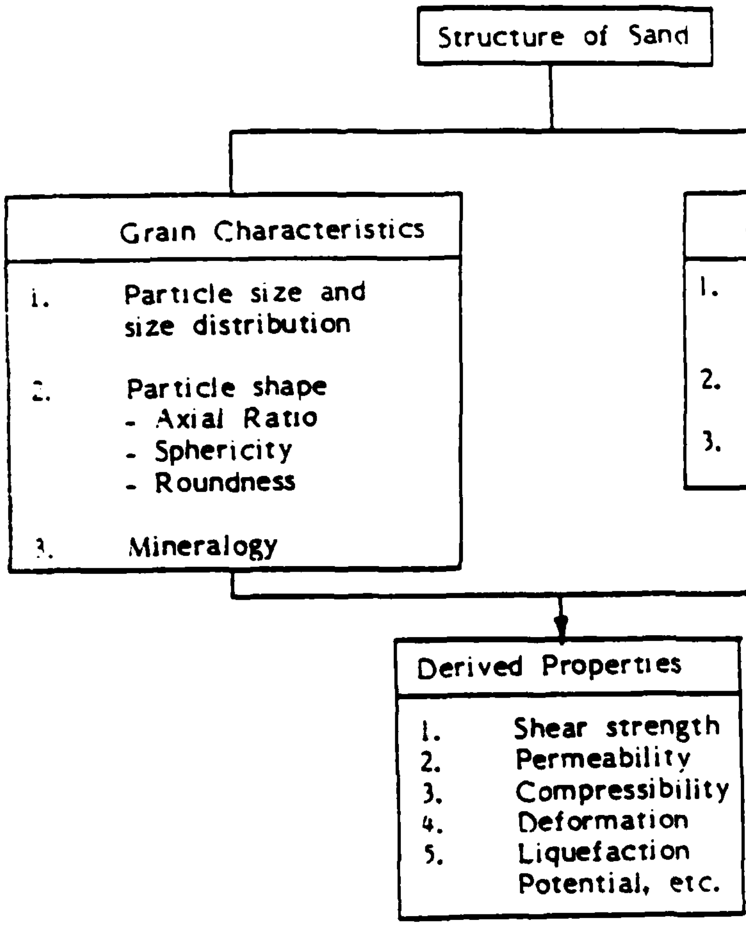

Figure 4 The Structure and the Derived Properties of Sand

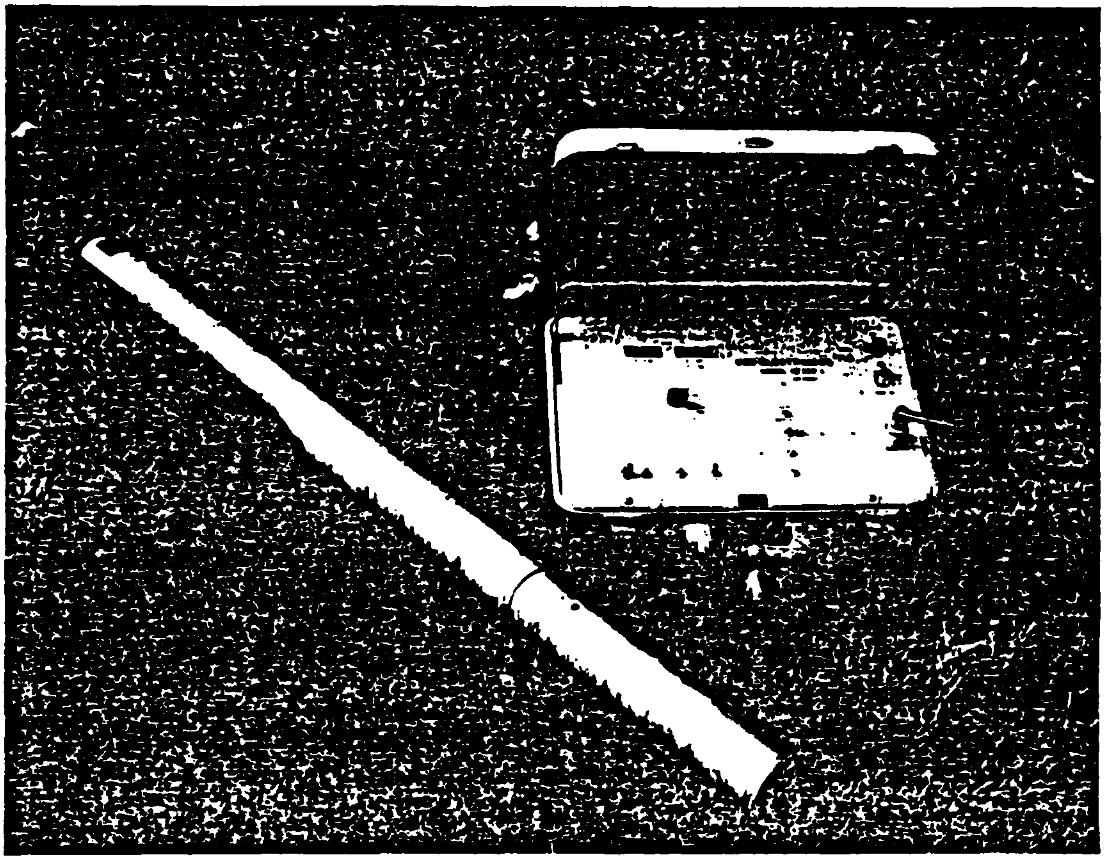

Figure 5 The Electrical Soil Probe

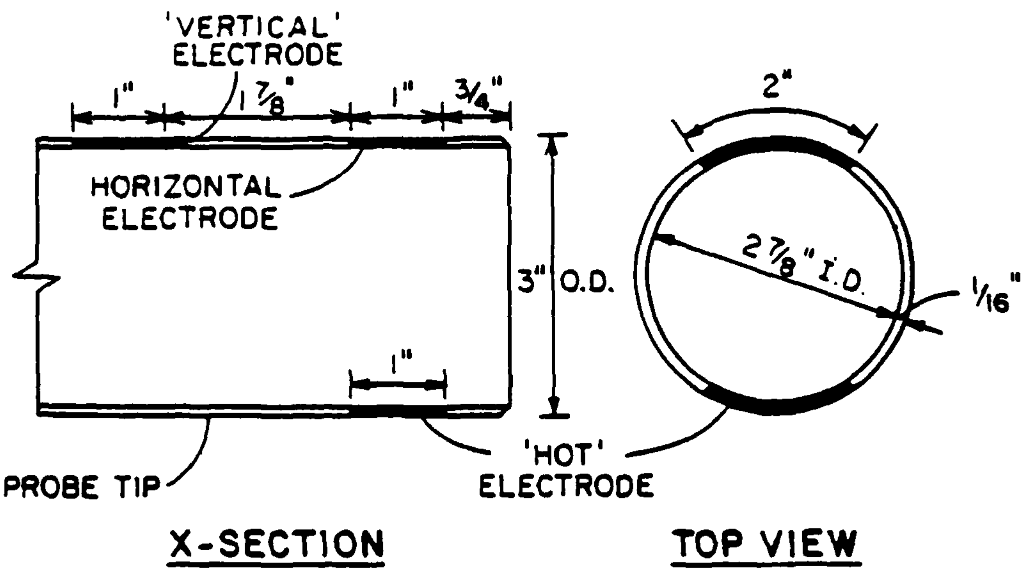

Figure 6 Schematic View of the Electrodes

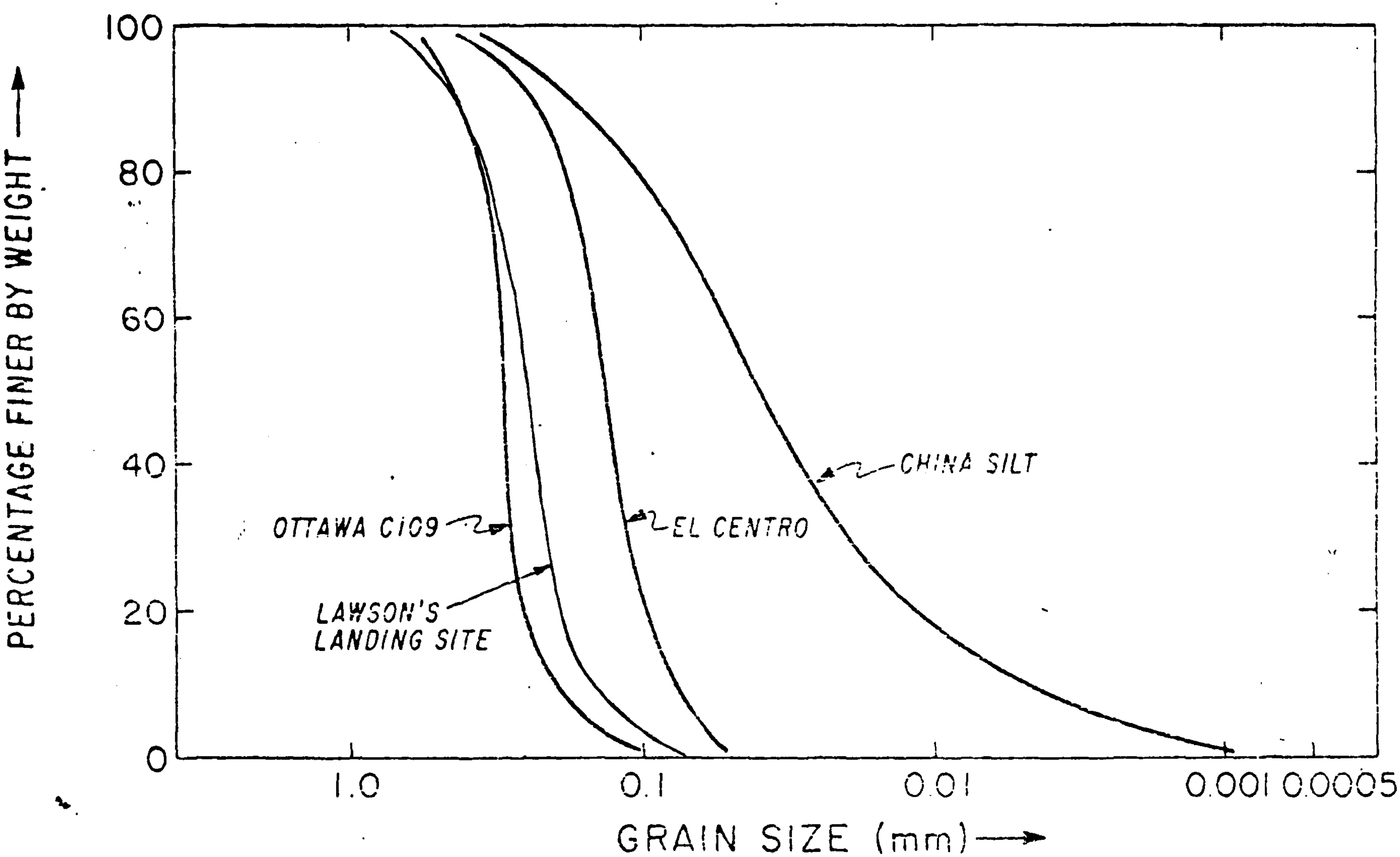

Fig. 7. GRAIN SIZE DISTRIBUTION FOR SOILS TESTED

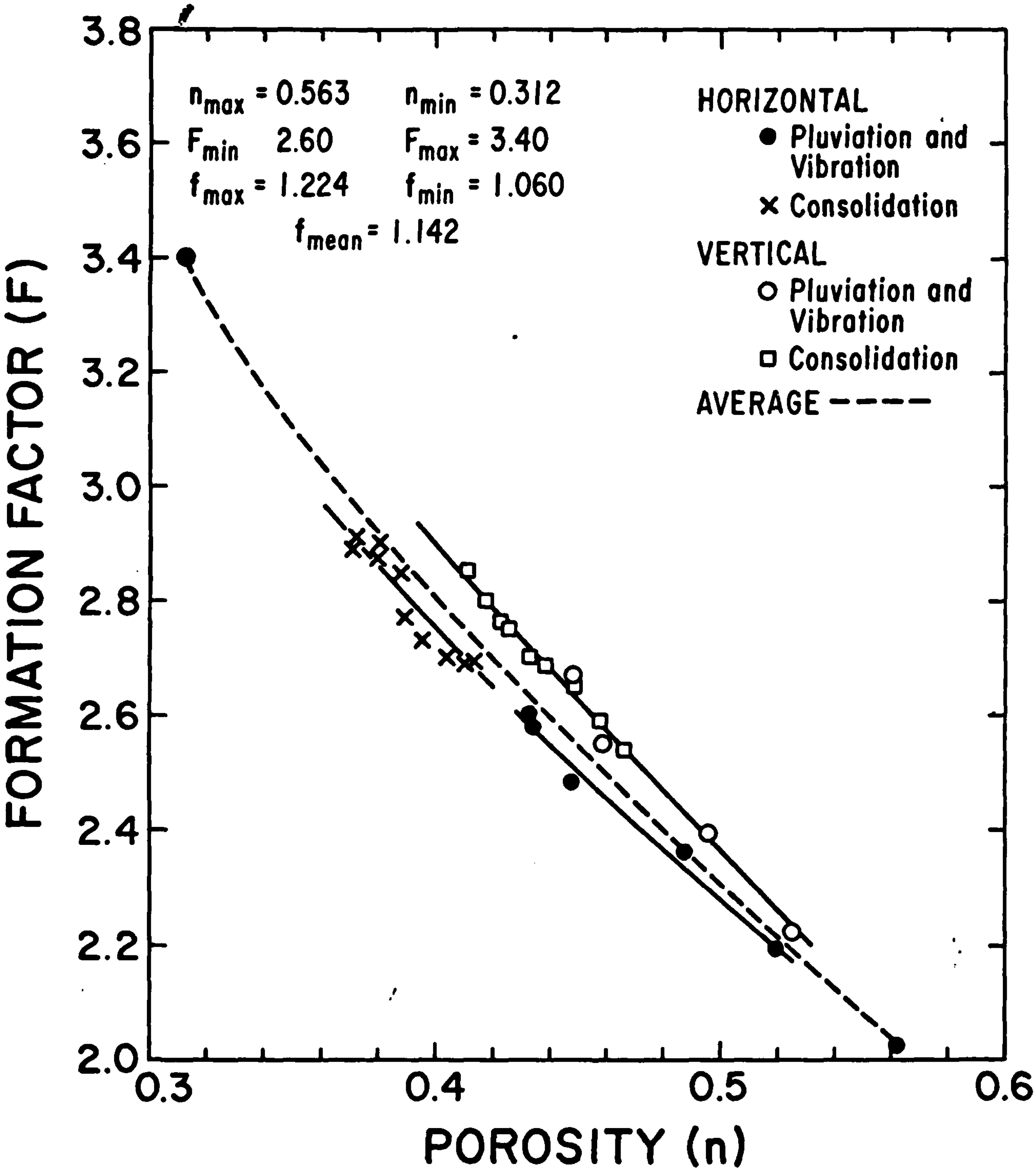

Fig. 8. FORMATION FACTOR–POROSITY RELATIONSHIPS FOR SAND FROM EL CENTRO SITE

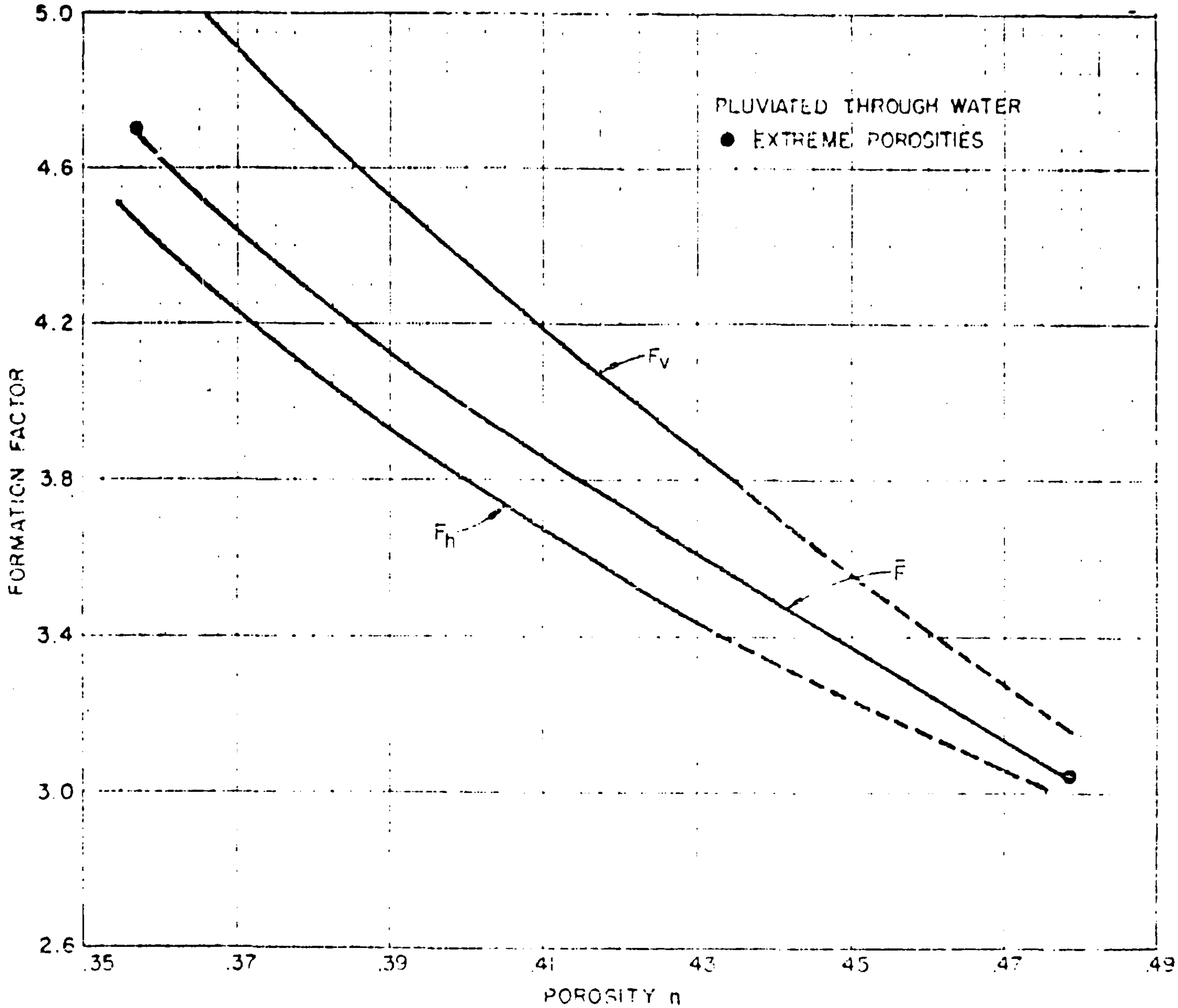

Fig. 9. Formation Factor vs Porosity Relationship for Lawson's Landing Site.

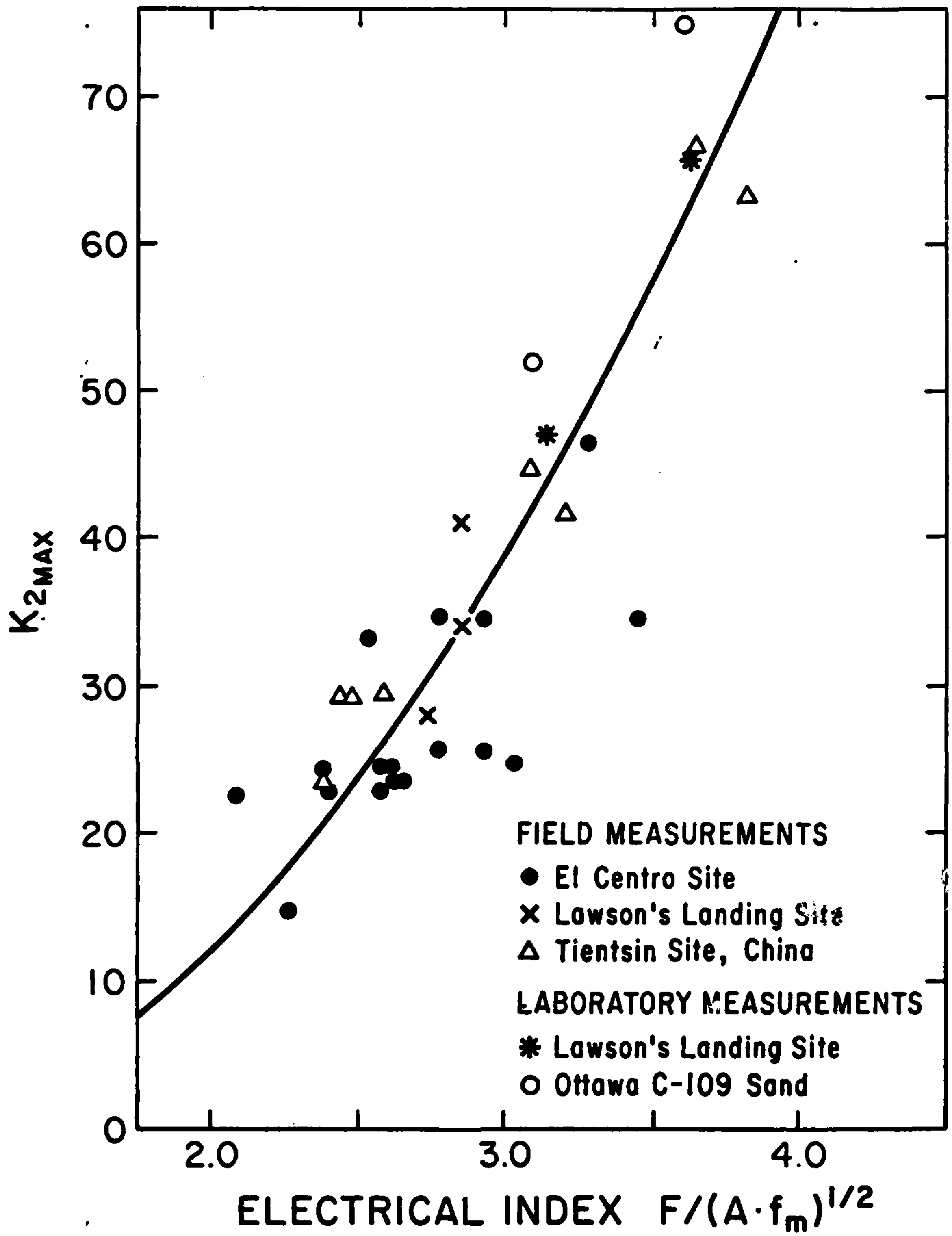

Fig. 10. RELATIONSHIP BETWEEN ELECTRICAL INDEX AND K_{2MAX}

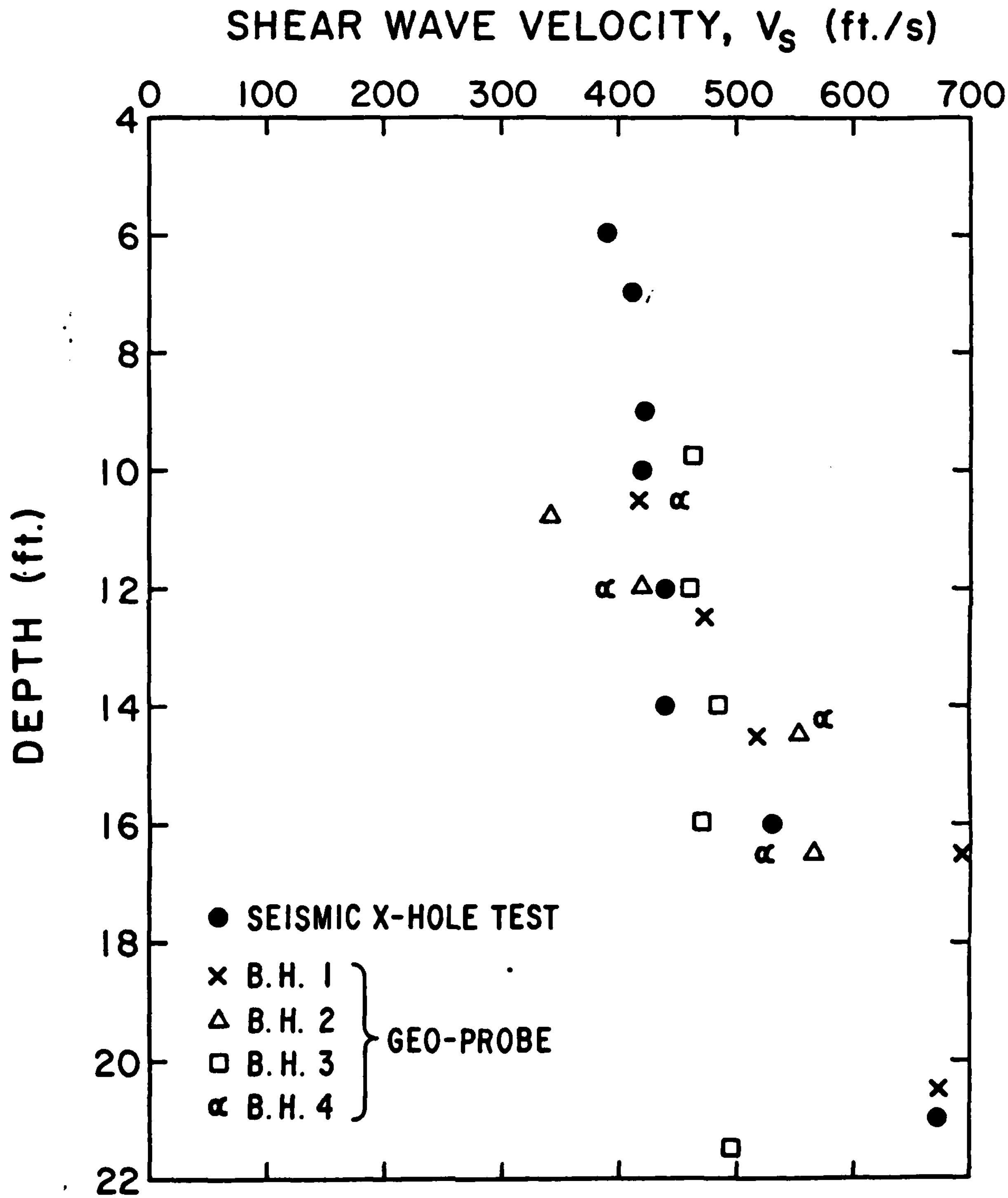

Fig. 11. COMPARISON OF SHEAR WAVE VELOCITIES OBTAINED FROM CROSS-HOLE MEASUREMENTS AND USING GEO-PROBE FOR EL CENTRO SITE

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